LIFE CYCLE COST ASSESSMENT OF INSECT BASED FEED PRODUCTION IN WEST AFRICA

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ABSTRACT

While there is a growing body of research investigating the technical feasibility and nutritional properties of insect based feeds (IBFs), thus far little attention has been devoted to gauge the economic implications of implementation. This study has investigated the economic performance of ex-ante modelled IBF production systems operating in the geographical context of West Africa. A Life Cycle Cost (LCC) analysis of recently published life cycle inventory (LCI) data served as a basis to analyse and compare the economic performances of IBF production systems using *Musca domestica* and *Hermetia illucens* reared on different substrates. To gauge the application potential of IBF in West Africa, estimated breakeven sale prices of IBFs were benchmarked against the customary market prices of conventional feeds. The results show that the economic performance of IBF production in West Africa is largely determined by the costs attributed to labour and the procurement of rearing substrates, attesting economic advantages to the production of *M. domestica* larvae by measure of breakeven price (1.28 – 1.74 EUR/ kg IBF) and LCC (1.72 – 1.99 EUR/ kg IBF). A comparison of the breakeven sale prices of IBF with market prices of conventional feeds suggest that IBF has potential to substitute imported fishmeal, but findings offer no support for conjectured economic advantages over plant based feeds.

1. INTRODUCTION

The increasing demand for fish and livestock products spurs global food producing sectors and complicates efforts to implement the 2030 Agenda for Sustainable Development (Hunter et al., 2017; United Nations, 2017). This is especially the case in economically disadvantaged regions where agricultural productivity is low and vulnerable to the effects of an ever-warming climate (Wheeler and von Braun, 2013). Future demand scenarios are expected to place further strain upon traditional food systems and thereby reinforcing malnutrition and environmental degradation However, the way changes in food demand manifest differs considerably between regions, depending upon agricultural characteristics and socioeconomic conditions (Godfray et al., 2010). Provided farmers in economically disadvantaged regions are able to capitalise on better sales opportunities, an increase in the demand of fish and livestock products might even help to improve food security and economic participation (Blanchard et al., 2017; Godber and Wall, 2014; Herrero and Thornton, 2013; Tscharntke et al., 2012; Wheeler and von Braun, 2013). Especially aquaculture and aviculture, providing food reserves in case of crop failure and products of increasing demand, could play a key role in this respect (Blanchard et al., 2017; Godber and Wall, 2014; Vervoort et al., 2013). However, with imported and traditional feeds becoming increasingly sought after and cost-prohibitive, most small-scale farming operations struggle to achieve necessary production increments, causing deficits in supply and sales opportunities for imports (Godber and Wall, 2014; Makkar and Ankers, 2014; Tscharntke et al., 2012).

Alternative feed sources that are locally grown and do not compete with demands for human consumption are considered a solution to these constraints (Adegoke and Abioye, 2016; Herrero et al., 2016; Makkar, 2015; Naylor et al., 2009). Against this background, recent research has proposed the use of dipteran insects (fly larvae) as an alternative protein feed (Sánchez-Muros et al., 2014; Smetana et al., 2016; van Zanten et al., 2015). The larvae of fly species, such as housefly (Musca domestica) or black soldier fly (Hermetia illucens), are rich in proteins and fatty acids of high nutritional value (i.e., similar to fishmeal) and early studies have proven the technical feasibility for production at scale (Devic et al., 2017; Henry et al., 2015; Kenis et al., 2018, 2014; Koné et al., 2017; Salomone et al., 2017; Sánchez-Muros et al., 2016; Smetana et al., 2016; van Zanten et al., 2015). However, although there is a growing body of research describing the production and nutritional performance of insect based feed (hereafter called IBF), the potential economic performance of IBF and the competitiveness with conventional feeds remains barely investigated (Halloran et al., 2016; Kenis et al., 2018). Part of this lack in understanding can be attributed to the novelty of the concept. Most current production systems are still in the early stages of development, operating in experimental setups to enable research and engineering optimisation of rearing procedures. These pilot-scale systems do not yet trade on success criteria, such as economy of scale effects, which complicates efforts to carry out an ex-ante evaluation of their economic feasibility (Kenis et al., 2018; Sánchez-Muros et al., 2016).

To overcome this limitation and contribute to the bridging of knowledge gaps, this study builds upon research of Roffeis et al. (2017), who used experimental data from rearing trials in West Africa to formulate the design and Life Cycle Inventory (LCI) of different small-scale IBF production systems. Applying the Life Cycle Cost (LCC) methodology to the published LCI data, this study explores the economic performance of three small-scale production systems outlined below, operating in the conditions of tropical West Africa;

(1) production of *M. domestica* larvae with chicken manure, inoculated through natural oviposition, i.e., attracting naturally occurring flies from the facilities' surroundings (hereafter named IER_A);

(2) production of *M. domestica* larvae with a mixture of sheep manure and fresh ruminant blood, inoculated through natural oviposition (hereafter named IER_B); and

(3) production of *H. illucens* larvae using chicken manure and fresh brewery waste (solid, protein-rich residues of the fermentation of grains in the beer making process), inoculated artificially, i.e., inoculated with larvae from a captive adult colony (hereafter named FfA).

The characterisation of the LCI models with site-specific cost information (i.e., converted to a value in Euros [EUR]) serves as a basis to analyse the economic performance of current production designs, identify cost-critical aspects of IBF production, and derive breakeven sale prices in order to assess the economic feasibility of IBF in West Africa.

The results of this study provide a first account of the economic implications of the implementation of IBF in West Africa and showcase the potential of applying life cycle thinking tools in an early stage of product development.

2. MATERIAL AND METHODS

2.1. Goal and Scope

The goal of this study is to ex-ante evaluate the economic feasibility of current small-scale IBF production systems operating in the geographical context of West Africa. The results are expected; to (1) elucidate critical economic aspects of prospective IBF production in West Africa; (2) provide a basis for trade-off analysis between different insect rearing systems (*M. domestica* and *H. illucens*) and rearing substrates; (3) project the commercial potential of IBF in West Africa; and (4) provide recommendations for future research and development activities in the field.

The main tasks undertaken were a comprehensive LCC analysis, described below, and a comparison of IBF breakeven sale prices with the market prices of plant based protein feeds, i.e. cottonseed meal, palm kernel meal and soymeal, as well as imported Peruvian fishmeal.

As the present study continues on research presented in Roffeis et al. (2017), it draws on data and methodology from that study to maintain coherence.

2.1.1. Geographical context

The IBF production models represent up-scaled system versions of different experimental rearing trials in West Africa, i.e. Ashaiman, Ghana (FfA system) and Bamako, Mali (IER systems) (Roffeis et al., 2017). The socio-economic conditions at the two sites are exemplary for West Africa. The population of the subcontinent is among the fastest growing in the world and projected to double from 290 million in 2010 to almost 600 million by 2050 (United Nations, 2015). The most important constituent of the West African economy is the agricultural sector, which employed about 60% of the working population in 2012 (Hollinger and Staatz, 2015). Agricultural production is dominated by small-scale farming operations that produce rain-fed crops, livestock, fruits and vegetables, often managed in integrated systems and grown next to one another (FAO et al., 2015; Hollinger and Staatz, 2015).

2.1.2. System boundaries

The system boundaries of the LCC analysis are in accordance with those set in the LCI analysis of Roffeis et al. (2017). The system under investigation comprises the sourcing of raw materials, the insect rearing process, the separation of IBF and residue substrate, and the processing of the final co-products. Here the term plant gate is synonymous for the provision of products to a generic market in West Africa, excluding transport efforts related to the marketing of processed products.

2.1.3. Functional unit and reference systems

The IBF systems are compared based on costs associated with the provision of 1 kg IBF and co-produced quantities of residue substrates (rearing substrate remaining after production of the larvae) to a generic market in West Africa. Here the reference unit of 1 kg IBF stands proxy for 1 kg whole dried larvae with a residual water content of less than 10% (Roffeis et al., 2017).

To gauge the feasibility of current production designs, the IBF systems are further compared by calculating breakeven sale prices of IBF, assuming that residue substrates qualify as marketable organic fertilizers. The breakeven prices of IBF were calculated as total production costs minus the hypothetical revenues from residue substrates sold at a conventional price of organic fertilizers for 15.70 EUR/ t (surveyed price in

West Africa, as applicable to November 2015). The calculated breakeven point designates the minimum sale price at which all costs of production are covered without generating profits.

Considering the calculated minimum sale prices as a measure of the commercial potential, the breakeven prices of IBF products (i.e., see section 2.2.3) are compared with market prices of conventional, protein-rich feeds. The economic performance of IBF is first compared with that of imported Peruvian fishmeal given their similarity in terms of nutritional properties and position in the trophic network (i.e., animal based feed). Additionally, in order to analyse the differences between animal and plant based feeds, the three IBF systems are benchmarked against press cakes of predominant oil crops, i.e. cottonseed meal, palm kernel meal and soymeal. The prices of conventional feeds represent customary market prices in West Africa, as surveyed in November 2015. Cross-checks with statistical records suggest that the West African market prices were in close proximity to the world market prices at that time (see supplementary material S1).

2.2. Life cycle inventory (LCI)

The investigated insect production models are retraced from earlier research by the authors Roffeis et al. (2017), which used experimental data from rearing trials in West Africa to formulate the design and LCI of three commercially scaled IBF production systems in the geographical context of tropical West Africa. The LCI data used for the economic assessment are presented in Table 1 and Appendix A.

Table 1. Life Cycle Inventory (LCI) of different insect based feed (IBF) production models according to Roffeis et al. (2017). Comparison of the generic IER_A, IER_B and FfA system by relevant material and energy flows associated with the provision of 1 kg IBF and co-produced quantities of residue substrate to a generic market in West Africa. Inventory items categorised as ‘manufacturing equipment’ and ‘Consumables & supplies’ are detailed in Appendix A, Table A1 – A3.

Life Cycle inventory (LCI)	**Unit**	**IBF production models**		
Inventory items		IER_A	IER_B	FfA
PRIMARY FACTORS				
Σ Land	**m^{2}a**	**0.04**	**0.03**	**0.05**
Fixed	m^{2}a	0.01	0.01	0.00
Variable	m^{2}a	0.03	0.02	0.05
Σ Built infrastructure	**m^{2}a**	**0.07**	**0.04**	**0.11**
Insect rearing | rendering	m^{2}a	0.06	0.03	0.10
Storage	m^{2}a	0.01	0.01	0.01
Σ Labour	**h**	**1.9**	**1.6**	**3.1**
Labour (untrained)	h	1.5	1.1	1.9
Labour (trained)	h	0.3	0.5	1.1
INETERMEDIATE FACTORS				
Σ Substrate	**kg**	**100.0**	**62.7**	**26.8**
Manure (chicken | sheep), dried	kg	40.0	22.8	6.3
Ruminant blood, fresh	kg	-	14.2	-
Brewery waste, fresh	kg	-	-	8.9
Sorghum bran (purging)	kg	0.1	0.1	-
Saw dust (purging)	kg	-	-	0.6
Water (substrate conditioning) [a]	l	59.9	25.6	11
Σ Water	**l**	**68.4**	**32.7**	**63.6**
Water (process)	l	59.9	25.6	13.9
Water (cleaning)	l	8.4	7.1	19.6
Water (separation)	l	-	-	30.2
Σ Energy	**MJ**	**0.7**	**0.7**	**3.3**
Nat. gas (burned in oven/ cooker)	MJ	0.7	0.7	3.3
Σ Transport	**km**	**0.1**	**0.8**	**0.4**
Motorbike	km	0.1	0.1	0.3
Commercial vehicle (3.5 - 7.5t)	km	-	0.7	-
Truck (7.5 - 16t)	km	-	-	0.1
OUTPUTS				
Σ Process emissions				
Waste water	l	8.4	7.1	49.8
Emission CH_4 (to air)	g	15.5	10.0	11.3
Emission N_2O (to air)	g	0.3	0.2	0.2
Emission NH_3 (to air)	g	2.8	1.8	2.1
Volatile solids (≤ 10 ųm, to air)	g	2.5	1.6	1.8
Σ Process products	**kg**	**29.0**	**17.0**	**8.1**
Residue substrate (fertilizer)	kg	28.0	16.0	7.1
IBF, dried [b]	kg	1.0	1.0	1.0
SCALE OF PRODUCTION	kg IBF/ d	12.0	12.0	9.6

[a] Water used for substrate conditioning (rearing substrate), accounted for under inventory item; ‘water’.

The generic modelling approach of Roffeis et al. (2017) facilitated a consistent comparison of the IBF systems and eased the characterisation with economic data (i.e., cost data in EUR value). All production cycles start with the sourcing of rearing substrates and end with the killing and drying of insect larvae, which are assumed to be fed as dried whole larvae (i.e., IBF, dried). The distinguishing features and functioning of the IBF production models are briefly described in the following sections.

2.2.1. IER production models

Roffeis et al. (2017) published LCI data of two production scenarios for *M. domestica* reared using natural oviposition. The generic IER_A and IER_B production systems were conceived as small commercially scaled production systems that are suitable for implementation in small hold farming operations in rural areas of tropical West Africa (see a description of the systems in Koné et al. (2017)). The IER_A and IER_B system differ from one another in the rearing substrate used. The IER_A rears *M. domestica* on a mixture of water and dried chicken manure. The rearing substrate in the IER_B is a mixture of sheep manure, fresh ruminant blood, and water. The IER systems share a similar process setup, which is organised around the same sequence of operational procedures, i.e. substrate conditioning, larval production, separation and drying. To keep transportation needs to a minimum, both production systems were assumed to be in close proximity to manure providing facilities (i.e. poultry farm and sheep feeding stables). The scale of the IER production systems was set at a daily output of 12 kg dried insect larvae (≤10% water), i.e., 4383 kg dried insect larvae annually (Roffeis et al., 2017).

2.2.2. FfA production model

The generic FfA system rears *H. illucens* on a mixture of brewery waste, chicken manure and water. Roffeis et al. (2017) conceived the FfA model as a small-scale production facility, suitable for providing feed protein to small hold aquaculture operations in tropical West Africa. The FfA system operates with artificial substrate inoculation, where substrates are inoculated with larvae from a captive adult colony (i.e. seed larvae). This results in a more complex process cycle of six interrelated unit processes, i.e. substrate conditioning, egg production, larvae production, pupa production, separation (i.e. harvest) and drying. The process comprises two interlinked production units, i.e. larval rearing and egg production, which rely on a number of adult colonies of different age. The egg production unit thus acts as a system-internal hub, where production of pupae and the scale of larval production are synchronized with the calibrated daily egg output. As for the IER systems, the production facility was assumed to be in close proximity to a poultry farm. The FfA production system was modelled within the limitations of maintaining the adult colony at a constant number of 20,000 adult flies, which equates to a daily output of 9.6 kg dried insect larvae (≤10% water), i.e., 3,506 kg dried insect larvae annually (Roffeis et al., 2017).

2.2.3. Background data

To characterise the IBF models with cost information, additional data were collected on: (i) economic inputs and outputs; (ii) wage levels; (iii) market prices of organic fertilizers and conventional feed products; as well as (iv) functioning and properties of regional markets and how insect production systems could be integrated in agricultural value chains. To retain a maximum of geographical distinction and characteristics of the original rearing trials, all IBF models were characterised with site-specific commercial information, such as typical land rents, transport charges, hourly wages of trained and untrained staff as well as prices for rearing substrates, gas, water and the production equipment used.

Price information of inputs and outputs were surveyed either desktop-wise or through investigations and interviews on-site. All prices were gathered in the respective national currencies, i.e. African Financial Community franc – CFA (IER systems) and Ghanaian cedi – GHS (FfA system), and reflect the site-specific market values of items during the third and fourth quarters of 2015 (see supplementary S1). Assuming that price relations will remain constant and independent from exchange rates, the conversion to EUR value was made using the exchange rate at the date of the survey (see supplementary S1). Working hours and wages draw on surveyed information, but have been calculated based on optimistic averages, assuming a customary hourly wage for trained and untrained staff of 0.72 EUR and 0.45 EUR/ h, respectively. A comprehensive overview of the prices used in the characterisation of the LCIs is provided in the supplementary material S1.

2.3. Impact assessment

2.3.1. Economic performance

The economic performance of the modelled IBF systems was assessed by application of the LCC approach, following the SETAC code of practice (Gluch and Baumann, 2004; Swarr et al., 2011). The LCC analysis was conducted for the full LCIs as published by Roffeis et al. (2017), which yielded a comprehensive cost breakdown structure of the production processes, i.e., leaving costs related to upstream and downstream processes unconsidered. The LCC results thus resemble a total cost assessment, taking the perspective of an economic actor at the place of the functional unit (e.g., insect farmer or feed producer).

2.3.2. Data Quality and Uncertainty

Applying life cycle thinking methodology in the phase of product development has inherent uncertainty (Aziz et al., 2016; Peregrina et al., 2006). In this study the uncertainty results mainly from the assumptions made in the background inventory data, i.e., market price information. As the surveyed price information does not permit any degree of variability (i.e., single point data), an uncertainty analysis was not executed. However, the influence of price assumptions on the assessment results was evaluated by means of a sensitivity analysis, in which the effects of schematic variations in wages and prices of organic fertilizer were evaluated.

3. RESULTS

3.1. Life cycle cost (LCC) analysis

The economic characterization results of the LCI models are summarized in Table 2. With a total of 1.72 EUR per kg IBF, the IER_A system has the lowest production costs (Table 1-2). Advantages over the IER_B and FfA systems are apparent in costs for transportation and manufacturing equipment. The IER_B system shows the second highest production costs, where the co-production of 1 kg IBF and 16 kg residue substrate incurs costs of 1.99 EUR (Table 1-2). Though lowest in labour costs and expenses for consumables and supplies, the IER_B system compares unfavourably in substrate and transportation costs. With a total of 2.48 EUR per kg IBF, the FfA system shows the highest production costs (Table 1-2). Marked disadvantages against the IER systems are apparent in the costs for built infrastructure, manufacturing equipment, labour, energy, and consumables and supplies.

Table 2. Economic characterisation of the life cycle inventory of different insect based feed (IBF) production systems. Comparison of the IER_A, IER_B, and FfA system by Life Cycle Costs (LCC) associated with the provision of 1kg IBF and co-produced quantities of residue substrate to a generic market in West Africa.

Life Cycle Cost (LCC)	**Unit**	**IBF production models** [e]			**Data source**
Inventory items		IER_A	IER_B	FfA	Foreground | background
PRIMARY FACTORS					
Σ Land	**EUR/kg IBF**	**<0.01**	**<0.01**	**0.01**	
Fixed	"	<0.01	<0.01	<0.01	(Roffeis et al., 2017) | SD [1]
Variable	"	<0.01	<0.01	<0.01	" | SD [1]
Σ Built infrastructure	**"**	**0.02**	**0.02**	**0.04**	
Insect rearing | rendering	"	0.02	0.01	0.04	" | SD [1]
Storage	"	<0.01	<0.01	<0.01	" | SD [1]
Σ Manufacturing infrastructure [a]	**"**	**0.01**	**0.03**	**0.07**	**" | Table B1 – B3**
Σ Labour	**"**	**0.93**	**0.83**	**1.67**	
Labour (untrained)	"	0.68	0.50	0.88	" | SD [1]
Labour (trained)	"	0.25	0.34	0.79	" | SD [1]
INETERMEDIATE FACTORS					
Σ Substrate	**"**	**0.64**	**0.66**	**0.37**	
Manure (chicken | sheep), dried	"	0.63	0.36	0.10	" | SD [1]
Ruminant blood, fresh	"	-	0.29	-	" | SD [1]
Brewery waste, fresh	"	-	-	0.27	" | SD [1]
Sorghum bran (purging)	"	0.01	0.01	-	" | SD [1]
Saw dust (purging)	"	-	-	<0.01	" | SD [1]
Σ Water	**"**	**0.03**	**0.02**	**0.00**	
Water (process)	"	0.03	0.01	-	" | SD [1]
Water (cleaning)	"	<0.01	<0.01	-	" | SD [1]
Σ Energy	**"**	**0.03**	**0.03**	**0.08**	" | SD [1]
Nat. gas (burned in oven/ cooker)	"	0.03	0.03	0.08	" | SD [1]
Σ Transport	**"**	**<0.01**	**0.38**	**0.17**	" | SD [1]
Motorbike	"	<0.01	<0.01	0.02	" | SD [1]
Commercial vehicle (3.5 - 7.5t)	"	-	0.38	-	" | SD [1]
Truck (7.5 - 16t)	"	-	-	0.15	" | SD [1]
Σ Consumables & supplies [b]	**"**	**0.04**	**0.03**	**0.07**	**" | Table B1 – B3**
OUTPUTS					
Σ Process emissions	**"**	**0.00**	**0.00**	**0.00**	
Waste water	"	-	-	-	" | SD [1]
Emission CH_4 (to air)	"	-	-	-	" | SD [1]
Emission N_2O (to air)	"	-	-	-	" | SD [1]
Emission NH_3 (to air)	"	-	-	-	" | SD [1]
Volatile solids (≤ 10 ųm, to air)	"	-	-	-	" | SD [1]
Σ Process products	**"**	**1.72**	**1.99**	**2.48**	
Residue substrate (fertilizer) [c]	"	0.44	0.25	0.11	" | SD [1]
IBF, dried [d]	"	1.28	1.74	2.37	" | Breakeven price
SCALE OF PRODUCTION	kg IBF/ d	12.0	12.0	9.6	"

[a] Durable inventory items that facilitate the production process (results are detailed in Appendix B, Table B1 – B3). [b] Inventory items that are used in the production process and replaced regularly (results are detailed in Appendix B, Table B1 – B3). [c] Revenue (i.e. cost coverage contribution) of residue substrates sold as organic fertilizer at a market price of 15.70 EUR/ t. [d] Breakeven price (i.e., cost price) of IBF, calculated as production costs less the hypothetical revenues from residue substrates. [e] All data presented are subject to rounding. [1] Surveyed data: market information and prices gathered upon surveys on-site in the third and fourth quarters of 2015 (see supplementary material S1).

A graphical representation of relevant cost flows helps to elucidate economically sensitive aspects of the IBF production systems (Figure 1). Expenses associated with the sourcing of rearing substrates (i.e. sum of substrate and transportation costs) are a relevant contributor to the LCC in all three systems (Figure 1).

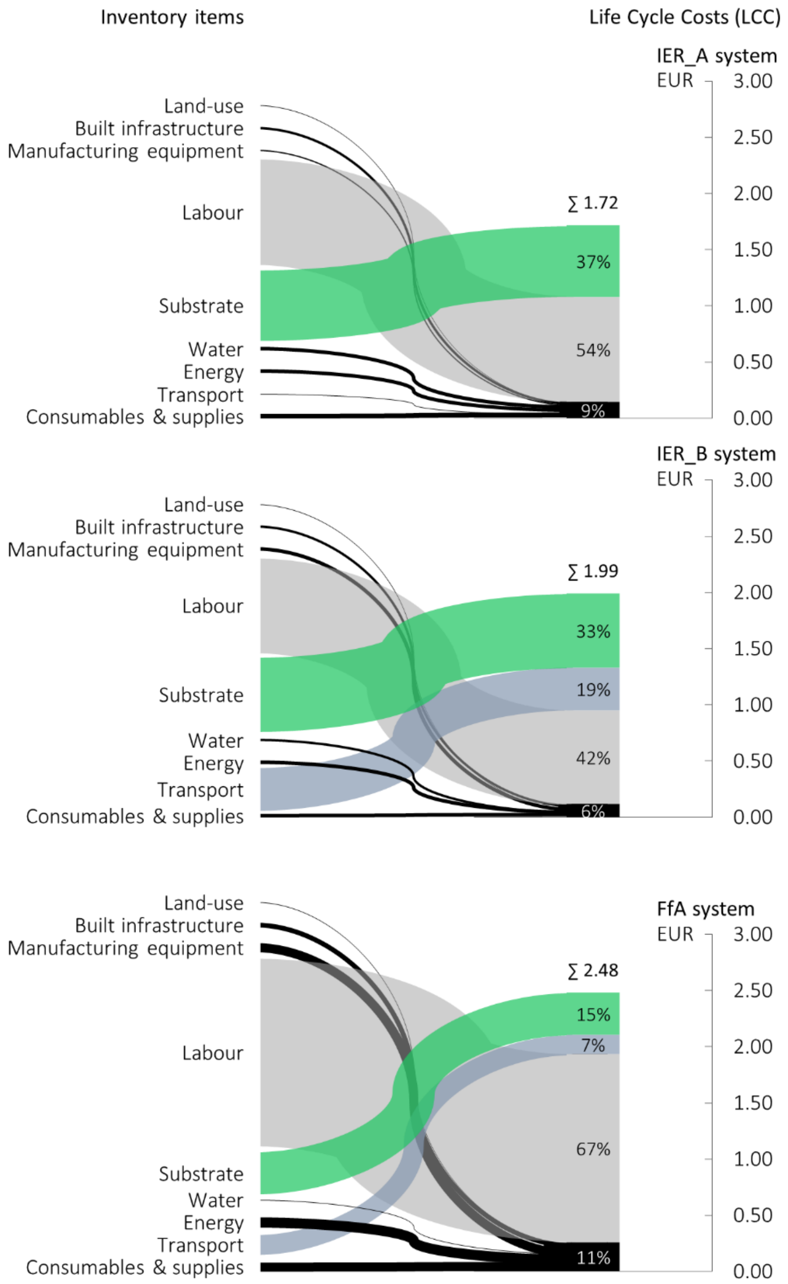

Figure 1. Economic characterisation of different insect based feed (IBF) production systems. Comparison of the IER_A, IER_B and FfA system by life cycle costs (LCC) associated with the provision of 1kg IBF and co-produced quantities of residue substrate to a generic market in West Africa. Breakdown of LCC results by contributions of relevant inventory items. The black arrows approximate cost flows of inventory items contributing less than 5% to the overall LCC results.

The substrate costs in the IER_A system are limited to the procurement of chicken manure, which, as for the residue substrate, is assumed to be traded as an organic fertilizer at a customary market price of 15.70 EUR/ t (Table 1). The co-production of IBF and residue substrate in the IER_A system requires 40 kg chicken manure, which equates to a cost of 0.64 EUR/ kg IBF, i.e., 37% of the total LCC (Table 1 and Figure 1).

The IER_B system, using a mixture 22.8 kg sheep manure and 14.2 kg ruminant blood/ kg IBF, shows the highest substrate related costs (0.66 EUR/ kg IBF). The sheep manure, otherwise appreciated as an organic fertilizer, is sourced at the same price as the chicken manure in the IER_A and FfA system (i.e. 15.70 EUR/ t), which causes 0.36 EUR/ kg IBF in substrate costs, i.e., about 55% of the total substrate costs. The remainder of 0.29 EUR/ kg IBF (about 45% of the total substrate costs) is attributed to the costs of ruminant blood (Table 1). Added to this are costs associated with the sourcing of ruminant blood (i.e. transport costs of 0.38 EUR kg/ IBF), which in total represent 52% of the total LCC (Figure 1). The lowest substrate related costs are found in the FfA system. The substrate costs of 6.3 kg chicken manure and 8.9 kg brewery waste total 0.10 EUR and 0.27 EUR/ kg IBF, respectively (about 15% of total LCC), while sourcing of brewery waste adds another 0.17 EUR/ kg IBF in transport costs, i.e., 7% of total LCC (Figure 1).

Labour costs, amounting to 42%-67% of the total process cost, are by far the highest cost factor in the IBF production systems. The highest share of labour costs (67%) are found in the FfA system, totalling 1.67 EUR/ kg IBF. Labour costs in the IER_A and IER_B system are considerably lower, amounting to 0.93 EUR/ kg IBF (54% of total costs) and 0.83 EUR/ kg IBF (42% of total costs) respectively (Figure 1).

A detailed breakdown of labour costs by salary structure and operational activities, as presented in Figure 2, offers a better understanding of the process features underlying the incurred labour costs.

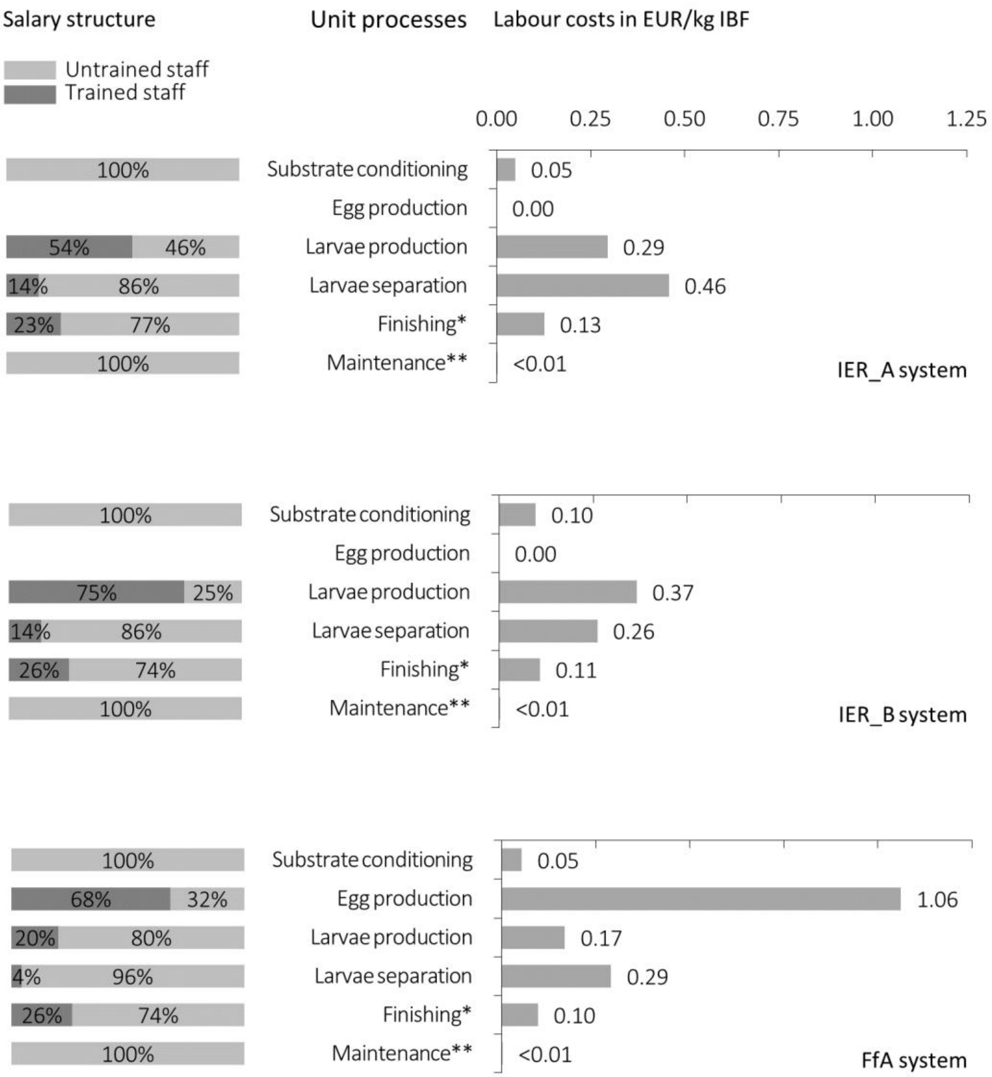

Figure 2. Breakdown of labour costs in different insect based feed (IBF) production systems. Comparison of the IER_A, IER_B and FfA system by labour costs associated with the provision of 1kg IBF and co-produced quantities of residue substrate to a generic market in West Africa. Breakdown of labour costs by salary structure, i.e., cost contribution through the employment of trained- and untrained staff paid 0.45 EUR/ h and 0.72 EUR/ h respectively, and unit processes, indicating the operational activities where costs are incurred. All figures presented are subject to rounding.

*Operational procedures leading to gut purging, killing, and drying of larvae.

** Labour costs relating to administrative tasks, maintenance and repair measures.

The labour costs in the IER_A system are largely due to the larval production step (0.29 EUR/ kg IBF), the separation of larvae and residue substrate (0.46 EUR/ kg IBF), and operational procedures leading to the purging (emptying of their guts), killing, and drying of larvae, i.e. finishing (0.13 EUR/ kg IBF). Trained staff perform 16% of the labour inputs, but due to a higher wage level, account for 27% of the total labour costs in the IER_A system (Table 1 and Figure 2). The highest cost contribution through trained staff can be found in the larval production and finishing processes (Figure 2).

The formation of labour costs in the IER_B system follows in principle the one of the IER_A system, although the handling of two substrate components (i.e., sheep manure and ruminant blood) increases labour costs in the substrate conditioning and larval production step (0.10 EUR/ kg IBF and 0.37 EUR/ kg IBF). The use of two substrate components also sets greater demands on the skills and experience of the operators, which is in turn reflected in the higher employment of trained staff (31% of the labour inputs) and their share in the overall labour costs (41%). A more favourable conversion efficiency, on the other hand, causes relative savings in the larval separation step (0.26 EUR/ kg IBF), as lower quantities of co-produced residue substrates (16 kg/ kg IBF) are separated (Table 1 and Figure 2).

The high labour costs of the FfA system are largely explained by labour inputs in the egg production unit. The operational activities relating to the maintenance of adult colonies and the constant production of seed larvae equates to labour costs of 1.06 EUR/ kg IBF, i.e., 63% of the total labour costs. About 47% (0.79 EUR/ kg IBF) of the labour costs in the FfA system are due to trained staff (Table 2), employed primarily in the egg production unit to ensure constant process flows. Associated management efforts and complex operational procedures using trained staff causes labour costs of 0.72 EUR/ kg IBF, which equals 68% of the labour costs in the egg production unit (Figure 2). The relevant contribution of trained staff in the FfA system is also shown in the labour costs associated with larval production and finishing processes. Here the management and supervision of operational procedures through trained employees account for 20% and 28% of the labour costs, respectively (Figure 2).

The observed differences between the IBF production models accentuate when systems are compared by breakeven prices of IBF (Table 1). In the IER_A system, the co-production of 28 kg residue substrate (i.e. organic fertilizer) generates revenues of 0.44 EUR/ kg IBF (26% cost coverage), which equates to a breakeven price of 1.28 EUR/ kg IBF (Table 1-2). The IER_B system, generating 0.25 EUR/ kg IBF in revenues (13% cost coverage) through the co-production of 16 kg residue substrate, arrives at a considerably higher breakeven price of 1.74 EUR/ kg IBF. The FfA system profits the least from the trade of residue substrates. Here the sale of 7.1 kg residue substrate forms 0.11 EUR/ kg IBF in revenues (4% cost coverage) and leads to a breakeven price of 2.48 EUR/ kg IBF (Table 1-2).

3.2. Sensitivity analysis

The cost contribution analysis illustrates the influence of substrate and labour costs to the overall LCC results. To analyse the influence of the underlying price assumptions, a sensitivity analysis was carried out in which the LCC results were recalculated under the conditions of varying wages and prices of manure and residue substrate (i.e., organic fertilizer). Figure 3 illustrates the possible realisations of the LCC results corresponding to wage levels for trained and untrained staff of (W1) -20% of BSL wage level; (BSL) baseline wage level; (W2) +20% of baseline level; and (W3) assuming equal pay for trained and untrained staff of 0.45 EUR/ h.

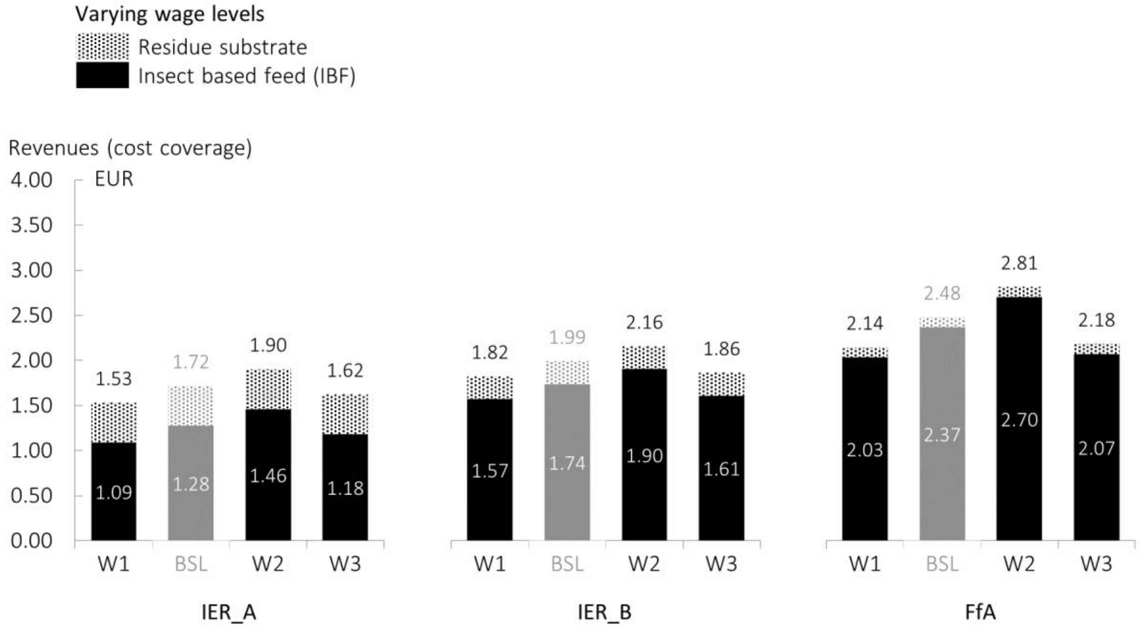

Figure 3. Breakeven prices of insect based feeds (IBF) under conditions of varying wage levels. Comparison of the IER_A, IER_B and FfA systems by estimated breakeven prices of IBF (i.e., cost price) corresponding to wage levels for trained and untrained staff of (W1) -20% of BSL wage level; (BSL) baseline wage level, assuming customary hourly wages for trained and untrained staff of 0.72 EUR and 0.24 EUR/ h, respectively; (W2) +20% of baseline level; and (W3) assuming an equal pay for trained and untrained staff of 0.45 EUR/ h.

The sensitivity with which the breakeven prices respond is in accordance with the relative contribution of labour costs to the system's overall LCC (compare Figure 1 and 3). The breakeven price of IBF in the IER_A system ranges from 1.09 EUR/ kg IBF (W1) to 1.46 EUR/ kg IBF (W2), i.e. 86% and 115% of the breakeven price in the BSL scenario. The LCC results of the IER_B system are less sensitive to a variation in wage levels. Due to a comparatively low share of labour costs, the estimated breakeven prices range from 1.57 EUR/ kg IBF (W1) to 1.90 EUR/ kg IBF (W2), which equates to a variation of about ± 10% compared to the BSL scenario (figure 3). The FfA system, with the highest share of labour costs (67% of the total LCC), shows a comparable response to changes in wage levels to the IER_A system. The variation of wages by -20% (W1) and +20% (W2) follows a variation in breakeven prices compared to the BSL scenario of -14% (2.03 EUR/ kg IBF) and +14% (2.70 EUR/ kg IBF), respectively (Figure 3).

The assumption of equal pay for trained and untrained staff (W3) results in a sizeable decrease in breakeven prices, although prices of IBF remain above the ones calculated in W1 (Figure 3). Given the high costs of trained staff, the FfA system shows the most sensitive response, where the breakeven price decreases by 23% (2.07 EUR/ kg IBF) as compared to the BSL scenario (Figure 3).

The effects of varying prices of manure and residue substrate on the system's LCC results are summarized in Figure 4. The price variations analysed include: (F1) zero economic value (i.e. manure and residue substrate are considered a true waste stream); (F2) 7.85 EUR/ t (-50% BSL); (BSL) baseline scenario, i.e., assuming a customary market price for organic fertilizer of 15.70 EUR/ t; and (F3) 23.55 EUR/ t (+50% BSL) (Figure 4).

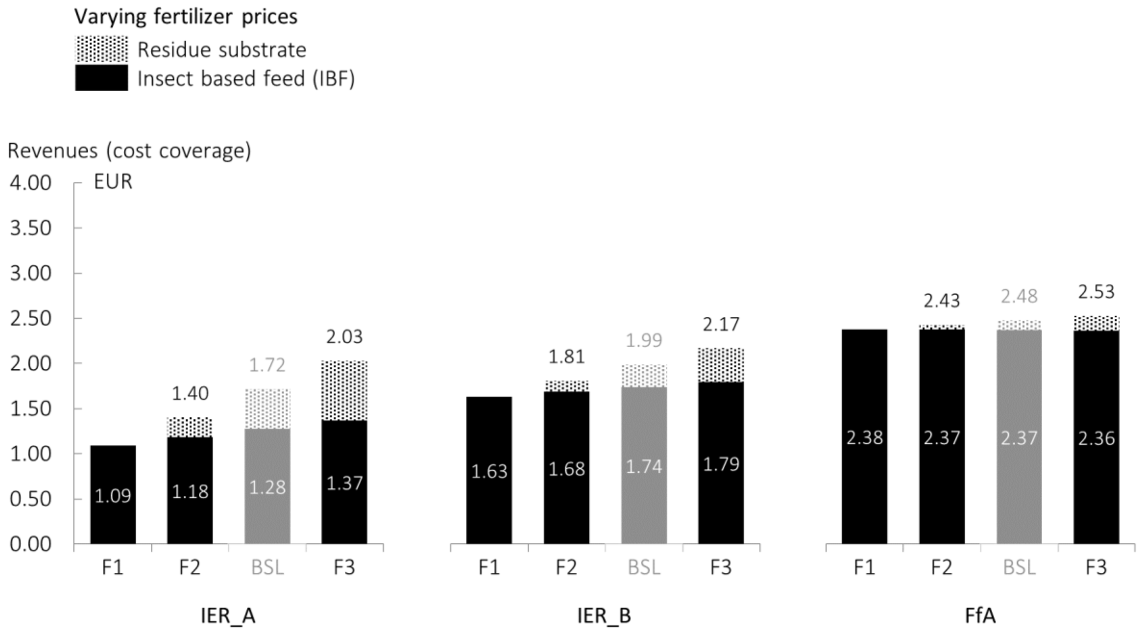

Figure 4. Breakeven prices of insect based feeds (IBF) under condition of varying market prices for organic fertilizer. Comparison of the IER_A, IER_B and FfA system by estimated breakeven prices of IBF (i.e., cost price) corresponding to fertilizer prices of (F1) zero economic value (i.e. considered a true waste stream); (F2) 7.85 EUR/ t; (BSL) customary market price of 15.70 EUR/ t, i.e., baseline scenarios as surveyed in West Africa in the third and fourth quarters of 2015; and (F3) 23.55 EUR/ t.

As price variations of organic fertilizer affect the price of manures (sheep and chicken), as well as traded residue substrates, the response of the breakeven prices are largely a function of the system's conversion efficiency. The IER_A system shows the highest variation in breakeven prices of IBF due to the comparatively low efficiency of conversion. An increase in fertilizer prices from 0 EUR/ t (F1) to 23.55 EUR/ t (F3) causes a variation of the breakeven price of -14% and +8% compared to the BSL scenario, respectively (Figure 4). In scenario F3 (23.55 EUR/ t fertilizer) the trade of residue substrate in the IER_A system realizes 0.66 EUR/ kg IBF in revenues, which equates to a cost coverage contribution of almost 33% (Figure 4). The IER_B system shows a similar variation in breakeven prices of IBF, although the increase from F1 to F3 is less pronounced, due to the higher conversion efficiency (Table 1 and Figure 4).

The lowest relative changes in breakeven prices are observed in the FfA system. As chicken manure constitutes a minor component of the substrate mixture, the increase in prices of organic fertilizer caused a slight decrease in the breakeven price. At a fertilizer price of 23.55 EUR/ t (F3), the trade of residue substrate in the FfA system generates 0.17 EUR/ kg IBF in revenues, which results in a breakeven price of 2.36 EUR/ kg IBF (Figure 4).

3.3. Economic feasibility assessment

To ex-ante assess the feasibility of current IBF production designs in West Africa, estimated breakeven prices (i.e. minimum sale prices) of the IBFs are compared with market prices of imported Peruvian fishmeal and commonly used plant based protein feeds, i.e. cottonseed meal, palm kernel meal and soymeal. The results of this comparative analysis are summarized in Figure 5.

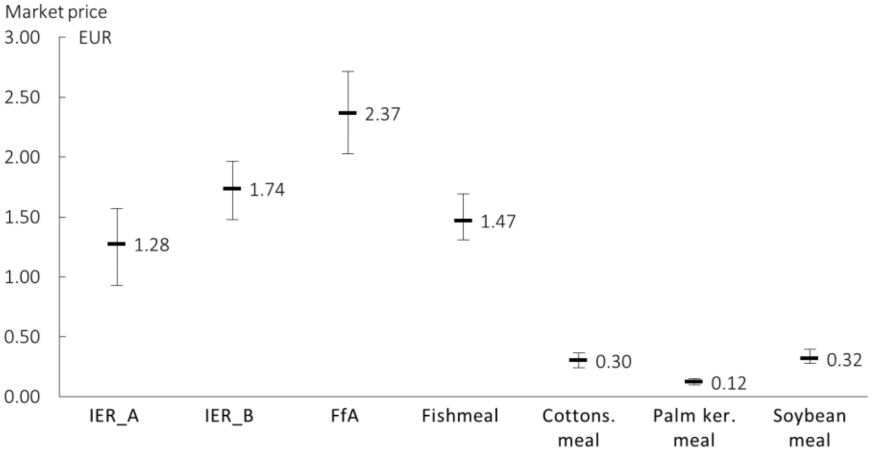

Figure 5. Comparison of estimated breakeven prices (i.e. minimum sale prices) of insect based feeds (IBF) with market prices of conventional feeds a generic market in West Africa. The error bars of the breakeven prices of IBF (IER_A, IERB and FfA system) indicate the possible range of price variations as follows from the sensitivity analyses (see Appendix C, Table C1 - C3). The error bars of fishmeal and soybean meal represent the range of monthly price variations between Sep 2012 and Jun 2017, as indicated by IndexMundi (2017a and 2017b). The error bars of the prices for cotton seed meal and palm kernel meal illustrate a default variation of ±20%.

The comparison of the breakeven prices of IBF with conventional feeds reveals large price differentials, especially between animal and plant based feeds (Figure 5). Ranging between 0.12 EUR/ kg DM (palm kernel meal) and 0.32 EUR/ kg DM (soybean meal), the market prices of plant based feeds are several times lower than the lowest-priced animal based feed product, i.e. IBF from the IER_A system (1.28 EUR/ kg DM).

The breakeven prices of IBF and market price of fishmeal, on the other hand, are comparable (Figure 5). The breakeven price of IBF in the IER_A system (1.28 EUR/ kg DM) settles below the surveyed market price of fishmeal (1.47 EUR/ kg DM). The IER_B system exceeds the market price of fishmeal by 0.27 EUR (1.74 EUR/ kg IBF), but compares favourably under the condition of low fertilizer prices and a 20% lower wage level (Appendix C, Table C2). At 2.37 EUR/ kg IBF, the FfA system has the highest breakeven price, way ahead of the other feed producing systems (Figure 5).

4. DISCUSSION

4.1. **Economic performance**

The results of the economic characterisation and cost breakdown analysis revealed economically sensitive aspects of the modelled production processes. The economic performance of IBF production in West Africa was found to be largely determined by the costs attributed to labour and to the procurement of rearing substrates. In the IER_A, IER_B and FfA systems, the sum of labour costs and the expenses associated with the sourcing of rearing substrates (i.e. sum of substrate and transportation costs) represented 91%, 94%, and 89% of the total costs, respectively (Figure 1). What attracts attention, however, is that the economies of relatively high conversion efficiency are seemingly offset by the higher costs for labour and rearing substrates. Roffeis et al. (2017) demonstrated that the use of a combination of rearing substrates with a high energy and protein content, as is the case in the IER_B and FfA system (i.e., fresh brewery waste and ruminant blood), benefits the system's conversion efficiency and thereby input efficiencies of relevant inventory items, such as land, built infrastructure, labour, substrate and water. However, a detailed LCI analysis also showed that rearing processes with more than one substrate component require a higher level of operator training (i.e., as indicated by the share of trained staff) and cause additional sourcing efforts, resulting in increased inputs for transportation and labour. This trade-off relationship resulted in comparable disadvantages to the economic performance of the IER_B and FfA system, as the high prices of trained labour and high quality substrates, such as brewery waste and ruminant blood, compensated for relative savings in the costs for land, built infrastructure, untrained labour and water (Figure 2 and Table 1).

The somewhat inverse relationship between conversion efficiency and economic performance becomes even more pronounced when systems are compared by breakeven prices of IBF (Table 1). The lower conversion efficiency of the IER_A system and the associated high output of residue substrate provides higher revenues from residue substrate, which in turn contributed to a favourable breakeven price of 1.28 EUR/ kg IBF (Table 1-2). The IER_B system co-produced lower quantities of residue substrate and arrived at a considerably higher breakeven price of 1.74 EUR/ kg IBF. Assessed with the highest conversion efficiency, the FfA system profits the least from the sales of residue substrates (0.11 EUR/ kg IBF in revenues) (Table 1-2).

In general, the production of *M. domestica* under conditions of natural oviposition provided economic advantage over the production of, artificially inoculated (i.e., inoculated with larvae from a captive adult colony) *H. illucens*. The interplay between egg and larval production involved a sequence of complex operation steps, requiring precise synchronization to achieve steady operation flows. This process organisation caused a high itemization and resulted in surpluses in costs for labour and manufacturing equipment, as well as consumables and supplies (see also Appendix B). Added to this, is the longer development time of *H. illucens* larvae, which also increased the inputs of intermediate and primary factors of production (Table 1).

Although results suggest that the IBF production through the exposure of substrates to naturally-occurring flies is more cost-effective than the production in a closed system, the latter shows a greater potential for improvement through economies of scale. The high production costs in the FfA systems are primarily due to labour inputs of trained staff in the egg production step (compare Figure 1-2). Given that the operational activities of trained staff members are to a large extent output-independent (i.e. management and monitoring efforts), a further upscaling of production permits the expectation of considerable cost digression effects.

While the LCC analysis showed that the differences in the economic performance of systems are mainly a function of rearing technique, rearing substrates, sourcing strategies and period of larval development, findings also hint towards a large influence of site-specific economic conditions (i.e., price levels). The possible effects of varying market conditions have been explored by means of a sensitivity analysis, the results of which are discussed in the following section.

4.2. **Sensitivity analysis**

A sensitivity analysis demonstrated a large variability of the LCC results in response to variations in wage levels and market prices of organic fertilizer (i.e., manure and residue substrate). Due to the high relevance of labour costs to the overall process costs, the economic performance of the IBF systems improved substantially with a decrease in labour costs. The assumption of equal pay for trained and untrained staff resulted in a similar effect, but particularly benefited the performance of the IER_B and FfA systems (i.e., those systems with a higher share of trained labour). Whilst the latter scenario is unlikely and contravenes efforts towards economic development it suggests potential benefits of further automation of IBF production processes, i.e., lower labour inputs and decrease in mean wage levels (Figure 3).

The varying prices of organic fertilizer showed a similar effect on the systems economic performances, although responses were more complex as price variations affect both the procurement prices of manure (sheep and chicken manure), and the retail prices of residue substrates (see also section 4.2). The IER systems showed a similar variation in breakeven prices, although the price increases in the IER_B system from 0 EUR/ t to 23.55 EUR/ t was less pronounced (i.e., higher conversion efficiency). Other than the IER systems, the breakeven prices of FfA slightly decreased in response to increasing fertilizer prices (Figure 4). Since chicken manure constitutes a minor component in the substrate mixture of the FfA system, the increase in fertilizer prices were paralleled with an increase in revenues from the trade of residue substrates, which in turn offset additional substrate costs.

The findings of the sensitivity analysis demonstrate the ambiguity of the LCC results, but also highlight the influence of socio-economic factors on the economic performance of IBF production. Given projected of wage increases in West Africa, the breakeven prices of IBF are likely to rise in the near future (Zhou and Staatz, 2016). However, it is safe to assume that changes in wage levels would likewise affect the market prices of other local feed production systems. The same applies to the costs of rearing substrates, which are expected to increase alongside all products in agricultural value chains in response to an increasing demand for food and feed (Hollinger and Staatz, 2015; Zhou and Staatz, 2016). Thus, if and how future market developments affect, or would be affected by, a widespread implementation of IBF in West Africa remains highly speculative.

4.3. Application potential

To gauge the feasibility of current IBF production designs in West Africa, a comparison was made between breakeven prices of IBF and surveyed market prices of imported Peruvian fishmeal and customary plant based protein feeds, i.e. cottonseed meal, palm kernel meal and soymeal. While breakeven prices represent an underestimation of the potential IBF market prices (i.e., include no profits), they indicate an important benchmark for a feasible market entry of IBF. The comparison showed, apart from substantial price differences between animal and plant based feeds, that the breakeven prices of IBF from the IER_A system are comparable with the market price of imported fishmeal. The IER_B system exceeds the market price of fishmeal, but would compare favourably under the condition of low fertilizer prices and a 20% lower wage level. The high breakeven price in the FfA system (2.37 EUR/ kg IBF) compared unfavourably to the market prices of all feed producing systems (Figure 5).

However, the comparison of the market prices per kg feed does not take into account the differences in the nutritional performance of feed products. Given differences in amino acid patterns, fatty acids, calories and fibre content of feedstuffs considered, it is likely that a comparative assessment would yield different outcomes when systems are compared based on the feed product’s nutritional values. The latter being strongly variable between the different livestock species, the only appropriate approach would be to compare feedstuffs based on their livestock-specific ileal digestibility (protein turnover per protein intake). Whilst such digestibility studies have been conducted for conventional feedstuffs, there is currently insufficient data available for IBFs to base an alternative FU definition on. Hence extended feeding trails are needed to evaluate the nutritional performance of IBF in proportion to conventional feeds.

Although the use of insects as feed has a long tradition in Africa among smallholder farmers (Kenis et al., 2014; Pomalégni et al., 2017), the technology of commercial production of fly larvae is still in its infancy. It is therefore noteworthy that the breakeven prices of IBF are already in proximity to those of the market prices of animal based feeds from well-established industries (i.e. fishmeal). Production systems for *H. illucens* and *M. domestica* of all sizes and forms are being developed worldwide, providing opportunities for increased efficiency and cost reduction (Koné et al., 2017; Pomalégni et al., 2017). Given the rapid advancements in the last few years, it is likely that future IBF production systems will produce at substantially lower costs through higher efficiency, scaling-up, and use of cheaper or free substrates and mechanisation.

4.4. **Implications for theory and practice**

While the LCC analysis is highly site-specific and associated with a considerable degree of uncertainty, the results offer valuable support to prospective practitioners, as well as future research and development activities aiming for a successful implementation of IBFs in tropical climates. However, because of the interdependence of input factors, statements on how to improve the system's performances can only be made for each input factor individually (i.e., rearing substrate, transport, labour etc.).

The LCC results demonstrate that the economic performance of IBFs is largely determined by the costs associated with the sourcing of rearing substrates (i.e. sum of substrate and transportation costs). As the most relevant mass flow in the production process, a successful implementation of IBFs crucially depends on the availability and regional price level of these resources. Here, the utilization of true waste streams, i.e. products or mass flows of no economic value that are not yet harnessed in other value chains, has proven most favourable. Substrates that are already traded as a food or feed, such as brewery waste and press cakes of oil crops, may benefit the systems' conversion efficiency but are less cost-effective and should only be used in minimal amounts, for example as a structural additive in rearing substrates. With regards to the economic relevance of transport processes, an application of IBF production systems in close proximity to substrate providing operations or markets appears recommendable. Where small-scale IBF systems form an integrated part of a livestock operation, considerations should also be given to feeding insects alive, as this would save costs associated with the drying/killing of larvae (i.e. labour and energy costs). The costs of labour, also identified as particularly performance-critical, are mainly a function of the prevalent wage level and the process organisation involved in the production of IBFs. To reduce the input of labour and associated costs, it requires further up-scaling and the development of automation technology that enables, for instance, workload reductions in the setup of rearing batches and manual separation of insects and residue substrates.

Following the basic assumptions underlying the concept of IBF, a widespread implementation of IBF production would aid sustainable development in two respects: (1) it provides an alternative protein rich feed source, that is locally grown and in no competition to the demands for human consumption (Joensuu and Silvenius, 2017; Van Huis et al., 2014); and (2) it opens an alternative avenue for the cost-effective recycling of nutrients from a range of different waste streams, including critical substrates such as food residues and slaughterhouse wastes (Dortmans et al., 2017; Koné et al., 2017; van Zanten et al., 2015). The study results support this notion, at least in terms of the system's economic performance and with reference to the geographical context of tropical West Africa. However, the extent to which the presented finding can be generalized requires further investigations. Special interest should be paid to the apparent trade-off between conversion efficiency and economic performance. It appears worth exploring if the inverse relationship is a system-specific phenomenon or a guiding principle in the recycling of biomass via IBF production. Against the background of today's sustainable development agenda, particular interest should also be given to the systems' environmental impact. Thus far publications investigating the environmental life cycle performance of IBFs, such as van Zanten et al. (2015), Prandini et al. (2015), Roffeis et al., (2015), Salomone et al. (2017), Smetana et al., (2016), or Payne et al., (2016), have only focused on IBF production in Europe. Given the substantial disparities in climate and socio-economic conditions, these studies hardly enable any conclusions to be drawn on the potential environmental ramifications in West Africa or other economically disadvantaged regions in tropical climates. To assess and examine conjectured sustainability advantages, the authors advise future research to investigate the environmental impact of the presented systems using environmental Life Cycle Assessment (LCA) methodology.

5. CONCLUSIONS

The production of IBFs offers a potential solution for strengthening food security and sustainable development in economically disadvantaged regions of tropical climates. To test the viability of this proposition, this study used LCC methodology to investigate the economic performance of three ex-ante modelled IBF production systems operating in the geographical conditions of West Africa.

The results show that the viability of IBF production in West Africa is largely determined by the costs attributed to labour and rearing substrates as well as the revenues generated from the trade of co-produced residue substrates. The combination of all three aspects resulted in economic advantages for the simplistic setups used in the production of *M. domestica* under conditions of natural oviposition. Artificial inoculation driving the production of *H. illucens* facilitated a high conversion efficiency but raised production costs, as the complex system setup and labour intensive process substantially increased inputs of labour and production infrastructure. However, owed to a higher share of output-independent cost factors, the production in a closed system showed a greater potential for improvement through economies of scale.

To estimate the commercial potential of IBF production in West Africa, a comparison was made between breakeven prices of IBF and surveyed market prices of imported Peruvian fishmeal and customary plant based protein feeds, i.e. cottonseed meal, palm kernel meal and soymeal. While IBFs showed considerable disadvantages in relation to plant-based feeds, the comparative assessment underpinned their potential of becoming a viable substitute for conventional animal based feeds (i.e., fishmeal).

The LCC analysis provides useful insights into the economic performance of IBFs and served as a basis to derive practical recommendations for prospective practitioners and future research and development activities aiming for a successful implementation of IBFs in tropical climates. However, the authors would like to remind readers of the prevailing uncertainties. The assessment of yet hypothetical production systems required assumptions and approximations in both foreground and background inventory data, as well as the use of proxy data when determining applicable market scenarios. Against this background, and taking into account that only a limited number of possible system designs are considered, the study findings do not support conclusive statements on the application potential of IBF in West Africa. Instead, the authors invite researchers and prospective insect farmers to recognise the study findings as an orientation to progress research and development activities and design individual, and locally adapted implementation strategy.

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